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Analytical Determination of Critical Crack Size in Solar Cells

C. P. Chen

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ABSTRACT

Although solar cells usually have chips and cracks, no material specifications concerning the allowable crack size on solar cells (e.g., Si or GaAs solar cells) are available for quality assurance and engineering design usage. Any material specifications that the cell manufacturers use have been developed for cosmetic reasons that have no technical basis.

Therefore, the Applied Solar Energy Corporation (ASEC) has sponsored a continuing program for the fracture mechanics evaluation of GaAs. As part of this research program, the work described here was carried out in the Applied Sciences and Microgravity Experiments Section of the Jet Propulsion Laboratory for the ASEC.

This publication utilizes fracture mechanics concepts to develop an analytical model that can predict the critical crack size of solar cells. This model indicates that the edge cracks of a solar cell are more critical than its surface cracks. In addition, the model suggests that the material specifications on the allowable crack size used for Si solar cells should not be applied to GaAs solar cells.

In this report, the analytical model was applied to Si and GaAs solar cells, but it would also be applicable to the semiconductor wafers of other materials, such as a GaAs thin film on a Ge substrate, using appropriate input data.

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I. INTRODUCTION

Cracking of solar cells is one of the leading causes of solar panel rejection and failure. Cracking of cells during field service and testing is expected to result from the extension of a critical preexisting crack or flaw under stress. The preexisting cracks — edge chips and surface flaws — are generated during ingot wafering and cell processing and handling. No material specifications concerning the allowable crack size for solar cells (e.g., Si or GaAs solar cells) are available for quality assurance and engineering design usage. Any material standards for the crack size on wafers used by wafer manufacturers have been developed for cosmetic reasons but lack a technical basis. In addition, solar cell manufacturers have noticed that the production yield for GaAs cells is much smaller than that for silicon cells when they have been handled in the same manner.

Fracture mechanics analyses were utilized to model and predict the minimum wafer thickness by conventional I.D. wafering [1] and rotated ingot I.D. wafering [2]. Fracture mechanics concepts can be also used to determine the allowable crack size in Si or GaAs solar cells when their fracture mechanics parameters are available.

In this publication, analytical equations for the critical crack size of a thin wafer were derived by using fracture mechanics. It is anticipated that these analytical models can provide a guideline for estimating the minimum allowable critical crack size of solar cells under several loading conditions. The analytical models were applied to silicon and GaAs, but would be also applicable to the large-area wafers of other materials, such as a GaAs thin film on a Ge substrate, using appropriate input data.

II. FRACTURE MECHANICS MODELING

Consider, for example, a thin wafer containing an edge crack, as shown in Fig. 1, or a surface crack, as shown in Fig. 2. If the preexisting cracks or flaws in the wafer do not exceed the critical size at the operating stress level, the wafer will sustain the first load application. However, with subsequent load applications and time at load, flaws will grow in size and may eventually attain the critical size, resulting in failure. The effect of subcritical crack growth on the acceptable crack size in a wafer is very important and should be studied separately.

However, it is of great importance to consider first the generic case of the critical crack size in semiconductor wafers. Fracture mechanics defines that, for a given operating stress level, the crack size required for the onset of rapid propagation and fracture is called the critical size. This critical size (a_c) in turn

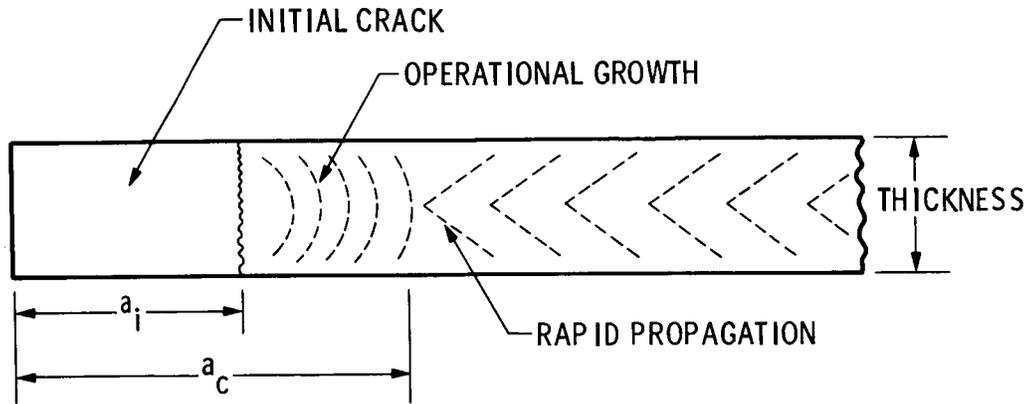


Fig. 1. Schematic Showing Edge Crack Growth in a Wafer

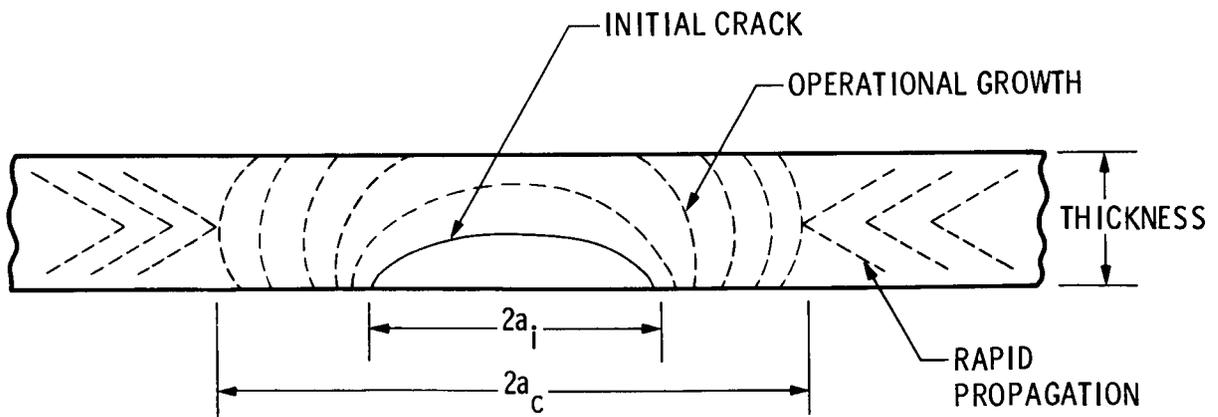


Fig. 2. Schematic Showing Surface Crack Growth in a Wafer

depends upon the critical values of the stress intensity factor (K_C) of the material in an equation [3, 4] as follows:

$$a_c = \frac{1}{Y^2} \left(\frac{K_C}{\sigma} \right)^2 \quad (1)$$

where σ is the applied stress and Y is a dimensionless constant that depends on the geometry of the loading and crack configuration. The Y value was determined to be approximately

$$Y \simeq \sqrt{\pi} \quad (2)$$

for a small surface crack, and

$$Y \simeq 1.12 \sqrt{\pi} \quad (3)$$

for an edge crack.

Fracture mechanics describes the crack extension in a material by three basic modes [5, 6] that correspond to the relative displacement of crack surfaces under stresses, as shown in Fig. 3. Mode I, in which crack surface displacements are perpendicular to the crack plane, tending to open the crack, is called the opening mode. Mode II and III are shearing displacements in the plane of the crack. Mode II is an in-plane shear in which the crack surfaces slide over one another perpendicular to the crack front, whereas Mode III produces tearing displacements that slide over one another parallel to the crack front.

Failure analysis has indicated that the cracking of solar cells in field service has been predominantly by Mode I, as shown in Fig. 4. In this figure, a crack extension appears to initiate at an edge chip of the cell under bending. Crack morphology on this wafer shows zigzags in a direction that appears to be the maximum bending stress direction. This zigzag cracking of the wafer was found [7] when an {100} silicon wafer was tested under a bending stress in the <100> crystalline orientation while the cleavage fracture of the silicon sample was in <110>. Crack morphology has also indicated [7] that the brittle fracture of semiconductors is controlled by crack initiation but not by crack propagation. A solar cell (wafer) subjected to a bending can be shown schematically as in Fig. 5. Mode II (in-plane shear cracking) is not likely to occur in a thin sheet material. However, Mode III (tearing), which is often used to break a thin sheet material, has been observed in cell cracking [6], as shown in Fig. 6. In this figure, the crack surfaces are seen to be sliding with respect to one another parallel to the leading edge of the cell. Cracking appears to be the result of a transverse force applied at the solder droplet near the edge of the cell which was supported on an elastic foundation. The loading condition of this cell can be described as "twisting," as shown in Fig. 7. Therefore, the mode of crack

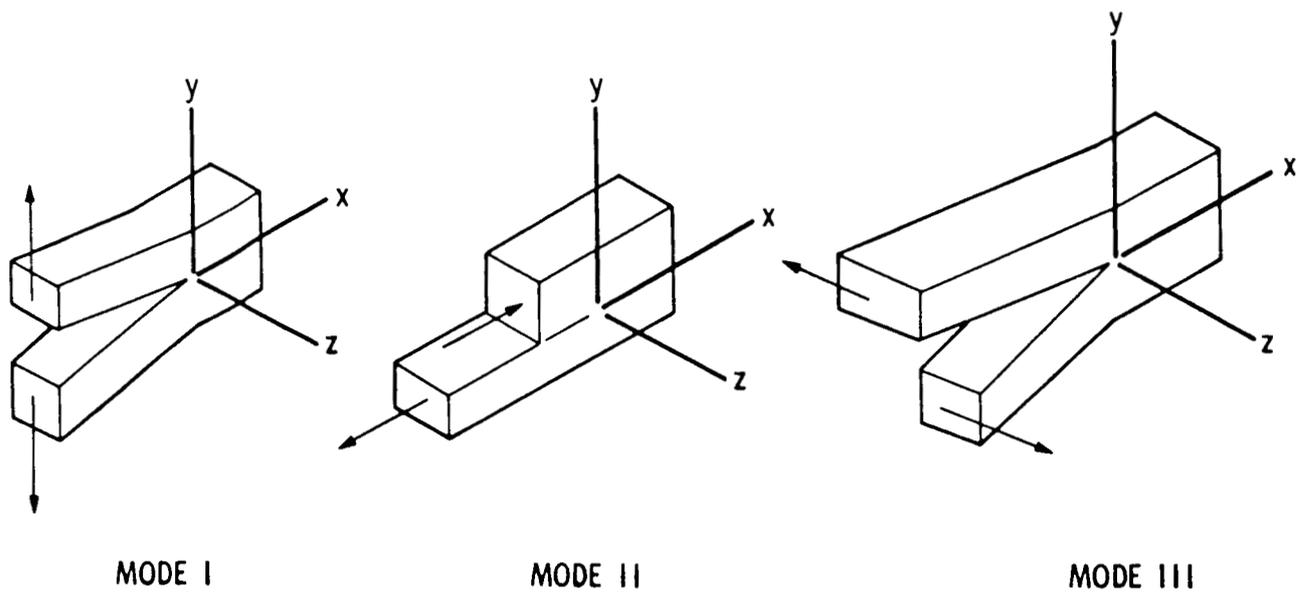


Fig. 3. Three Basic Modes of Crack Surface Displacement

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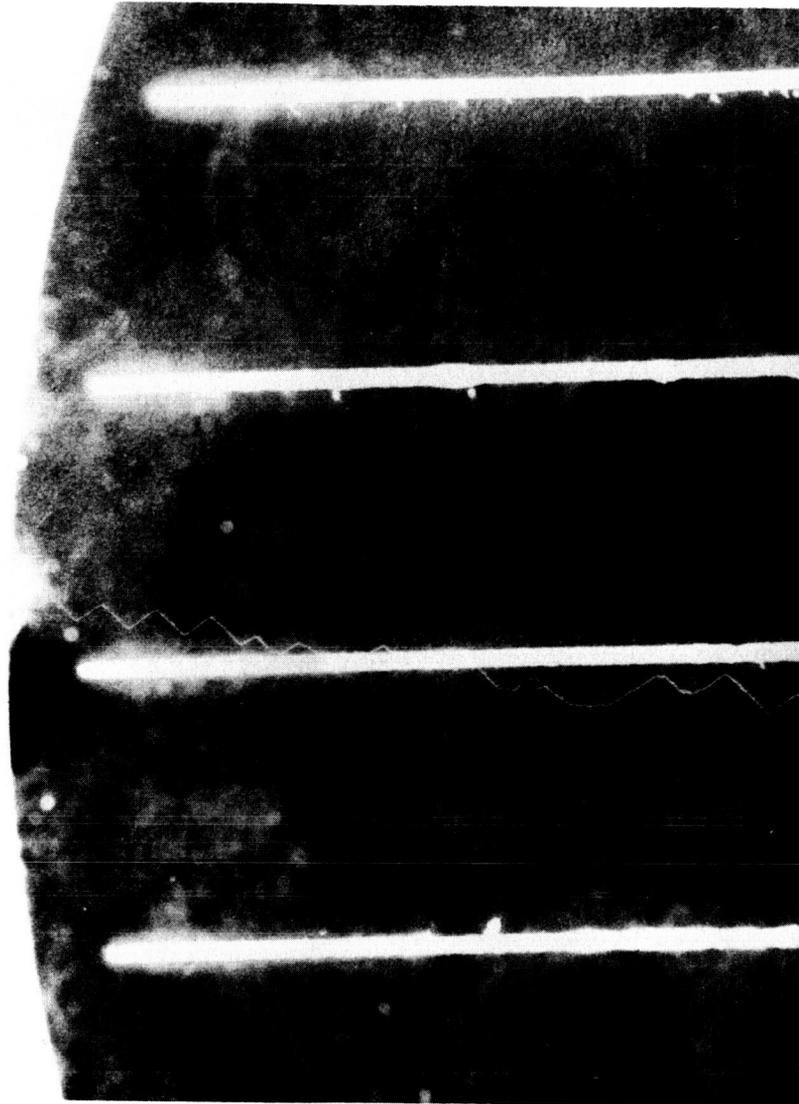


Fig. 4. Typical Mode I Cracking in a Solar Cell Crack Initiated at an Edge Chip

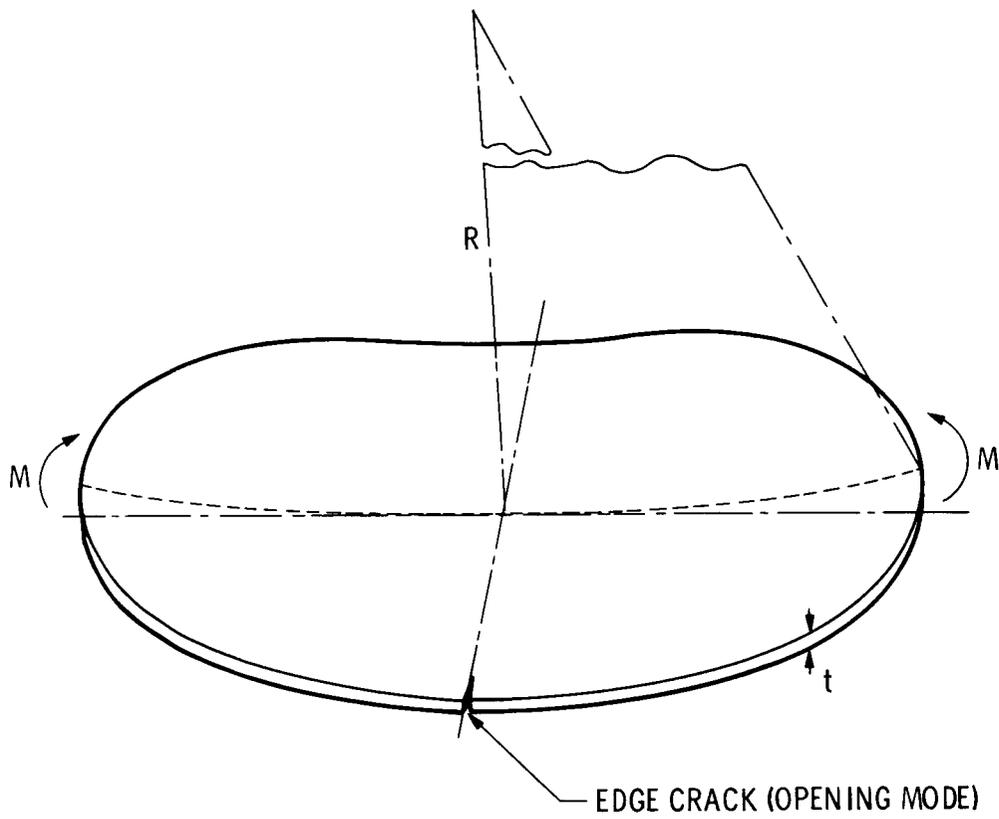


Fig. 5. Wafer Subjected to Pure Bending

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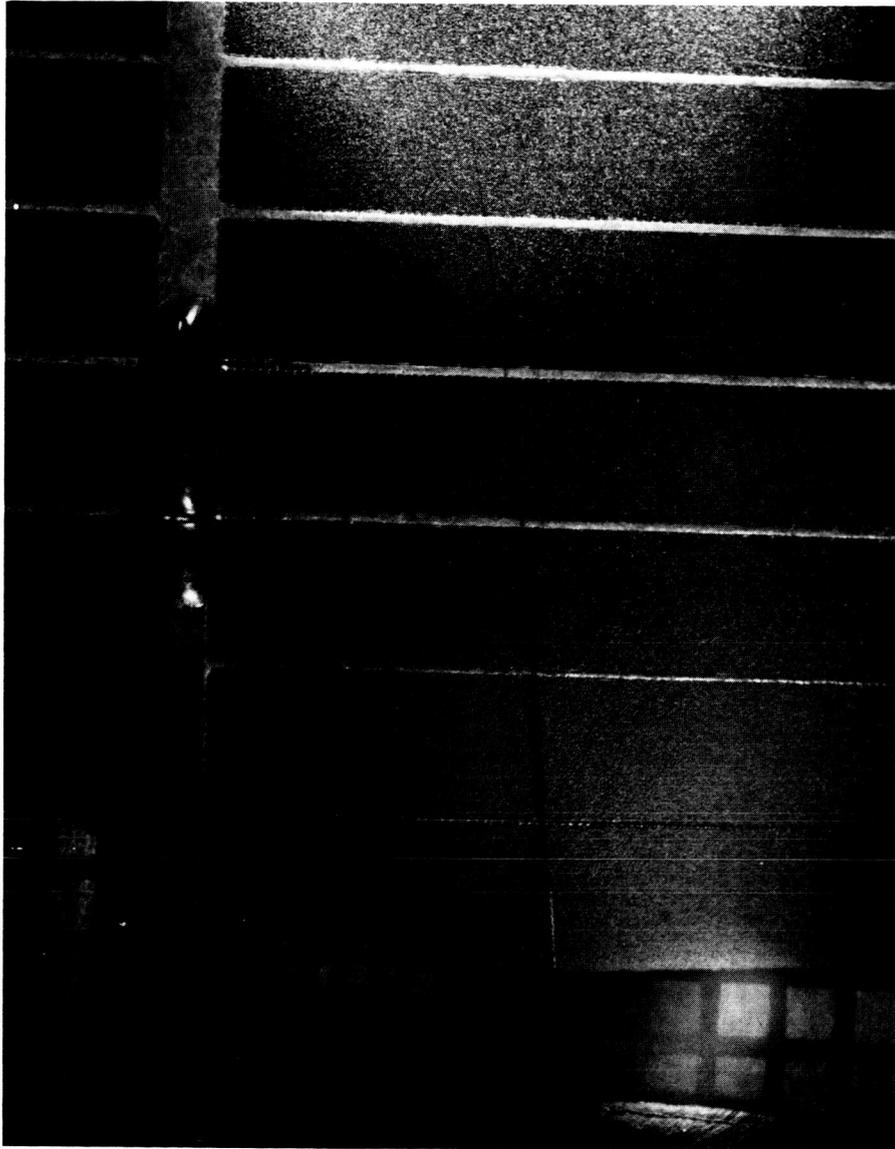


Fig. 6. Typical Mode III Tearing Form of Cracking in a Solar Cell

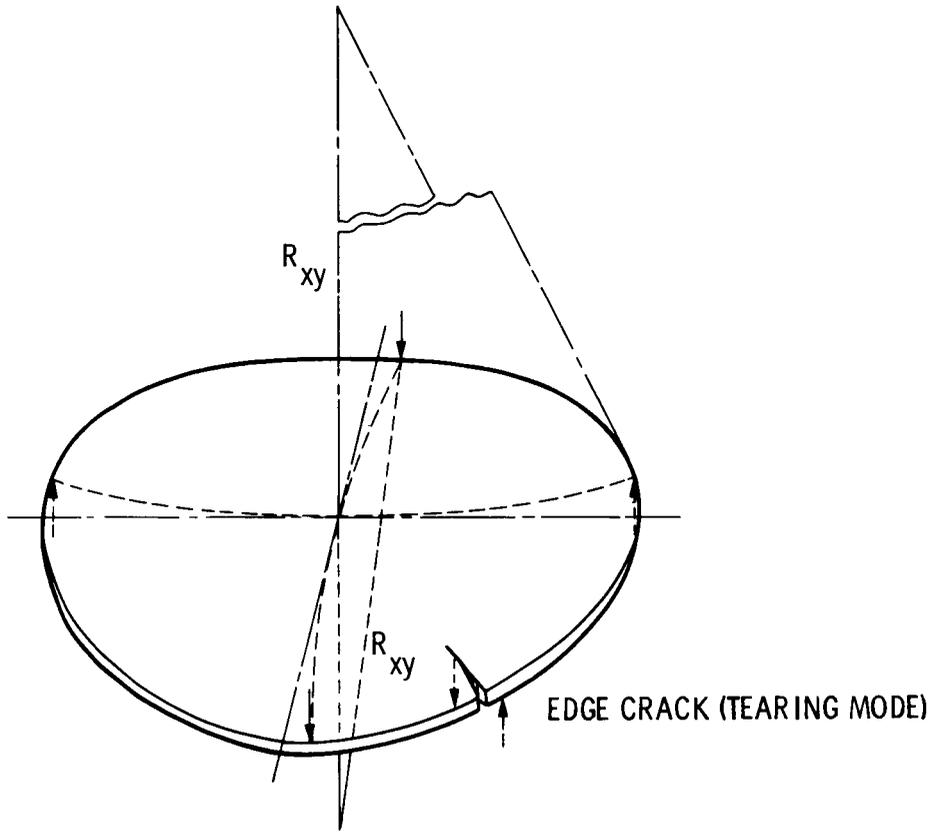


Fig. 7. Wafer Subjected to Twisting

extension in a thin wafer under bending and twisting will be considered as follows in the next two sections.

A. Bending

Consider a wafer subjected to a pure bending, M , as shown in Fig. 5. The nominal stress in the surface of the wafer is

$$\sigma = \frac{6M}{t^2} \quad (4)$$

where t is the thickness of the wafer. Integrating Eq. (4) into Eq. (1), we have

$$a_c = \frac{1}{Y^2} \left(\frac{t^2 K_{IC}}{6M} \right)^2 \quad (5)$$

where K_{IC} is the critical stress intensity factor for the extension of the opening mode (Mode I). K_{IC} is also called the fracture toughness of the material. This equation has been verified analytically by Paris and Shih [5], and experimentally by Erdogan et al. [8] using a crack in a thin plate of brittle material under bending.

As shown in Fig. 5, a thin wafer is subjected to a bending moment (M) and is deformed to a radius of curvature ($1/R$). The relationship between the bending moment (M) and bend radius (R) is expressed [9] as follows:

$$M = -D \left(\frac{1}{R} \right) \quad (6)$$

where D = the flexural rigidity of the wafer. For an isotropic thin wafer under cylindrical bending, as in Fig. 5, the rigidity is given [9] as

$$D = \frac{E t^3}{12(1 - \nu^2)} \quad (7)$$

where E = Young's modulus and ν = Poisson's ratio. Integrating Eq. (7) into (6), one obtains

$$M = - \frac{E t^3}{12(1 - \nu^2)} \left(\frac{1}{R} \right) \quad (8)$$

Integrating this equation into Eq. (5), the critical crack size of a thin wafer under pure bending can be calculated by an equation as follows:

$$a_c = \frac{4(1 - \nu^2)^2}{\gamma^2 E^2} \left(\frac{K_{IC} R}{t} \right)^2 \quad (9)$$

B. Twisting

Now, consider a wafer subjected to a pure twist as shown in Fig. 7, where four equal vertical forces are applied at the edges of the wafer: two diagonally opposite forces acting upwards and the other two acting downwards. In this case, the extension of an edge crack, as in Fig. 7, is expected to be the crack surfaces sliding with respect to one another parallel to the leading edge. This type of crack propagation is called the tearing mode or Mode III. The critical stress-intensity factor corresponding to this fracture mode is K_{IIIc} . Therefore, the relationship between the crack length and stress in Mode III can be written as

$$a_c = \frac{1}{\gamma^2} \left(\frac{K_{IIIc}}{\sigma_s} \right)^2 \quad (10)$$

where σ_s is the transverse shear stress resulting from the applied twist moment, M_{xy} . The twist moment per unit element of the plate can be expressed [9] as

$$M_{xy} = - \int \sigma_s z dz = 2 D_{xy} (1/R_{xy}) \quad (11)$$

where D_{xy} = the twisting rigidity of the wafer and $1/R_{xy}$ = the twisting radius of curvature.

Eq. (11) can be rewritten [9] as

$$\sigma_s = - 2 G t (1/R_{xy}) \quad (12)$$

where G = the shear modulus of the material and

$$G = \frac{E}{2(1 + \nu)} \quad (13)$$

Integrating Eqs. (12) and (13) into Eq. (10), the crack length in a wafer under twisting can be written as

$$a_c = \frac{(1 + \nu)^2}{\gamma^2 E^2} \left(\frac{K_{IIIc} R_{xy}}{t} \right)^2 \quad (14)$$

Eq. (14) expresses the critical crack size of a thin wafer under twisting as a function of the fracture mechanics parameters.

III. APPLICATION OF THE ANALYTICAL MODELS

As mentioned before, flaws in a material under stress may grow in size as a result of subcritical crack growth. The subcritical crack growth rate in GaAs was measurable [10] because the bonds of Ga-As were found to have not only covalent binding but also a large degree of "ionicity." However, experimental evidence [11, 12] indicated that no subcritical crack growth in silicon can be observed because the Si-Si bond is completely covalent. The determination of the acceptable crack size on a wafer in considering the effect of subcritical crack growth is beyond the scope of this report. It is of great importance to consider first the generic case of the critical crack size in semiconductor wafers.

Eqs. (9) and (14) will be utilized to evaluate the critical crack size in single-crystal solar cells, such as silicon and GaAs, under typical loading conditions. A special application of these models to a Ge substrate coated with a GaAs thin film will be also discussed.

A. Silicon and Gallium Arsenide Solar Cells

The appropriate material property and fracture mechanics data are required to use these analytical models to predict the critical crack size in the solar cells. The available fracture mechanics data for single-crystal silicon and GaAs are given in Table 1. The calculation of the critical crack length under bending and twisting is discussed in the following sections.

1. Bending

The fracture mechanics evaluation indicated that the minimum K_{IC} value of silicon was $0.82 \text{ MN/m}^{3/2}$ in cleavage plane {111}, while single-crystal GaAs has a minimum K_{IC} of $0.31 \text{ MN/m}^{3/2}$ in cleavage plane {110}, as shown in Table 1. Integrating the appropriate material property data and K_{IC} values from Table 1 into Eq. (9), the critical crack size equations can be rewritten as follows:

For Si in {111},

$$a_c = 0.697 \times 10^{-10} (R/t Y)^2 \quad (15)$$

Table 1. Fracture Mechanics Data for Single-Crystal Silicon and GaAs in the Major Crystalline Orientations

	Si	Ref.	GaAs	Ref.
$E_{\langle 100 \rangle}$	$1.28 \times 10^{11} \text{ N/m}^2$	[13]	$0.89 \times 10^{11} \text{ N/m}^2$	[17]
$E_{\langle 110 \rangle}$	$1.69 \times 10^{11} \text{ N/m}^2$	[13]	$1.25 \times 10^{11} \text{ N/m}^2$	[17]
$E_{\langle 111 \rangle}$	$1.90 \times 10^{11} \text{ N/m}^2$	[13, 14]	$1.44 \times 10^{11} \text{ N/m}^2$	[17]
ν	0.18	[13]	0.3	[17]
K_{IC} in {100}	$0.95 \text{ MN/m}^{3/2}$	[15]	$0.43 \text{ MN/m}^{3/2}$	[17]
K_{IC} in {110}	$0.90 \text{ MN/m}^{3/2}$	[15]	$0.31 \text{ MN/m}^{3/2}$	[17]
K_{IC} in {111}	$0.82 \text{ MN/m}^{3/2}$	[15]	$0.45 \text{ MN/m}^{3/2}$	[17]
K_{IIIC} in {111}	$2.22 \text{ MN/m}^{3/2}$	[16]	No data available	

For GaAs in {110},

$$a_c = 0.204 \times 10^{-10} (R/t Y)^2 \quad (16)$$

Let us consider the crack in the Si wafer first. Substituting Eqs. (2) and (3) into Eq. (15), the critical crack size can be expressed as follows:

For a surface crack,

$$a_c = 0.22 \times 10^{-10} (R/t)^2 \quad (17)$$

For an edge crack,

$$a_c = 0.18 \times 10^{-10} (R/t)^2 \quad (18)$$

Similarly, the critical crack sizes in GaAs wafers from Eq. (16) are expressed as follows:

For a surface crack,

$$a_c = 0.065 \times 10^{-10} (R/t)^2 \quad (19)$$

For an edge crack,

$$a_c = 0.052 \times 10^{-10} (R/t)^2 \quad (20)$$

Referring to Figs. 1 and 2, it should be noted that the a_c expressed in Eqs. (17) and (19) represents one-half of the total length of a surface crack, while the a_c in Eqs. (18) and (20) represents the full length of an edge crack. In order to determine the minimum critical crack size in wafers, the edge crack is, therefore, more critical than the surface crack. The edge crack size will be focused on below. The critical edge crack sizes as a function of bend radius and wafer thickness for single crystal silicon and GaAs are plotted in Fig. 8.

2. Twisting

The Mode III crack extension in single-crystal silicon was also found in the {111} cleavage plane. Integrating the K_{IIIc} value and the material property data of silicon into Eq. (14), the critical crack size can be calculated as follows:

For a surface crack half length,

$$a_c = 0.059 \times 10^{-10} (R_{xy}/t)^2 \quad (21)$$

For an edge crack full length,

$$a_c = 0.047 \times 10^{-10} (R_{xy}/t)^2 \quad (22)$$

The allowable critical edge crack size as a function of the twist radius for several silicon wafer thicknesses is plotted in Fig. 9. Since the K_{IIIc} value of GaAs is not available, the equations for the critical crack size of a GaAs wafer under twisting cannot be determined.

B. A Germanium Substrate Coated With a GaAs Thin Film

Since GaAs has been found to be more fragile but to have superior electronic properties than Si and Ge, composite materials for solar cells as well as the electronic and optical devices integrating GaAs and a substrate with large-area, lightweight, and high-strength crystals, such as Si or Ge, have been examined. Considering the compatibility of the lattice parameter and thermal expansion coefficient of GaAs and substrate materials, a Ge substrate appears to be the leading candidate for potential GaAs integrated circuit (IC) applications.

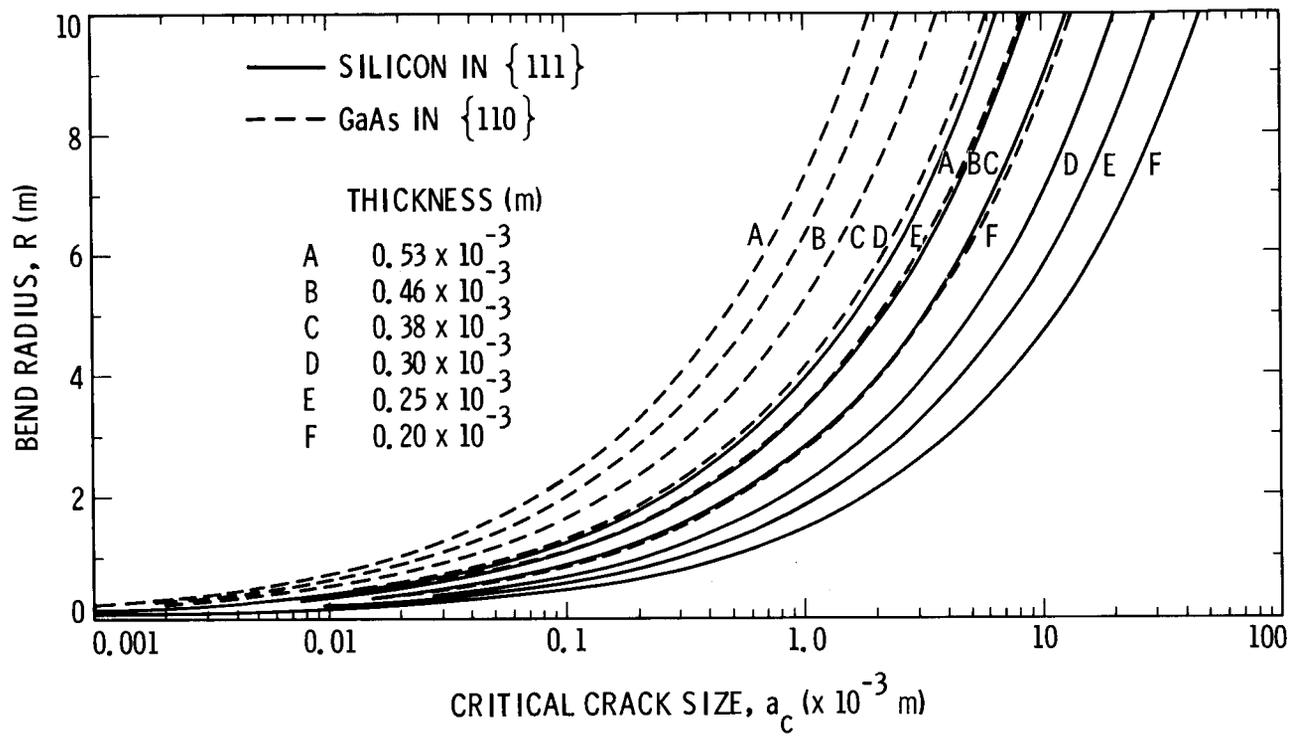


Fig. 8. Critical Edge Crack Size as a Function of the Bend Radius and Wafer Thickness for Silicon and GaAs Solar Cells

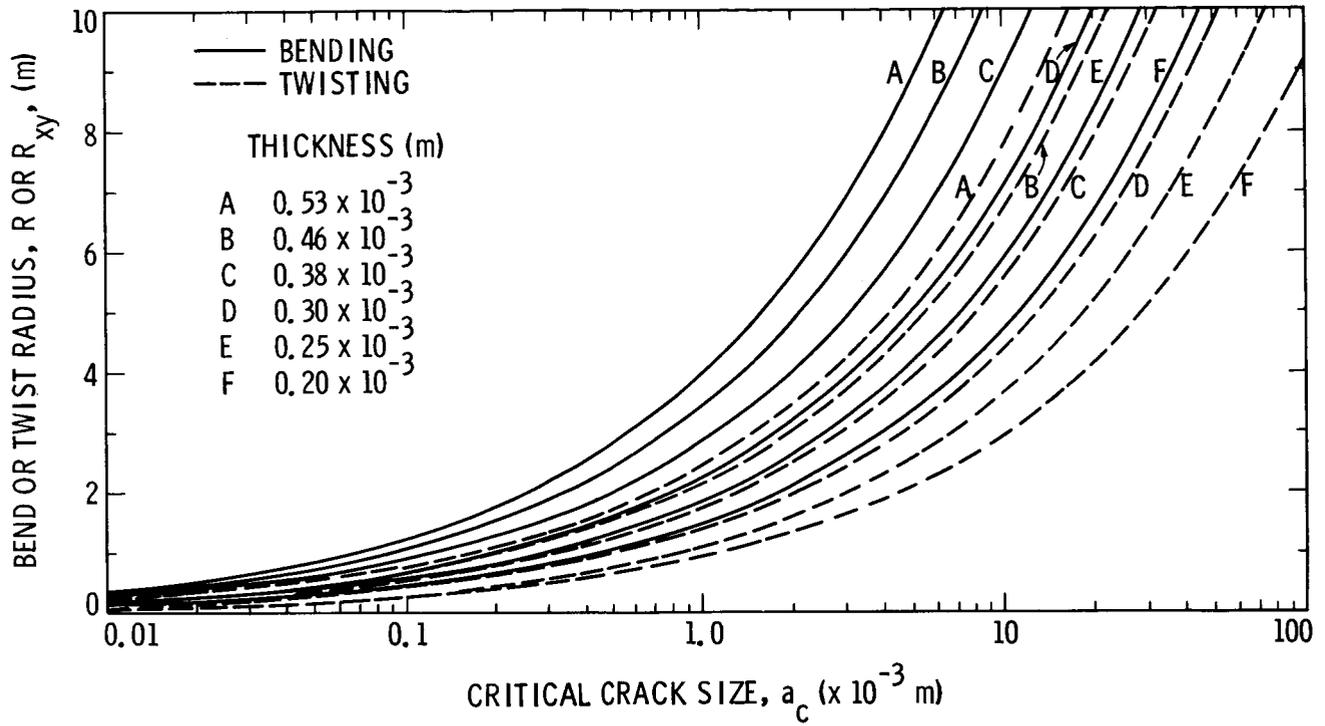


Fig. 9. Critical Crack Size in Silicon Wafers as a Function of the Bending or Twisting Radius for Several Wafer Thicknesses

The thickness of the GaAs thin film on the Ge substrate is in the order of several microns (e.g., 5×10^{-6} m), while the thickness of the Ge substrate is approximately 0.1×10^{-3} m. Therefore, the strength of the GaAs thin film coated Ge devices is controlled by the strength of the Ge wafer. A literature search on the fracture mechanics data of germanium indicated that the surface energy of Ge was measured [18] by a cleavage method. The minimum fracture surface energy of Ge was measured in the {111} cleavage plane to be:

$$\gamma_{\{111\}} = 1,060 \text{ ergs/cm}^2 \text{ (1.06 N/m),} \quad (23)$$

and

$$E_{\{111\}} = 14.0 \times 10^{11} \text{ dynes/cm}^2 \text{ (1.4} \times 10^{11} \text{ N/m}^2) \quad (24)$$

Using these data, the critical stress intensity factor or fracture toughness (K_{IC})* of Ge in the {111} planes is calculated to be:

$$K_{IC}(\text{Ge}) = 0.545 \text{ MN/m}^{3/2} \quad (25)$$

Table 1 notes that $K_{IC}(\text{Si}) > K_{IC}(\text{Ge}) > K_{IC}(\text{GaAs})$.

The Poisson's ratio of Ge reported [13] was:

$$\nu = 0.16 \quad (26)$$

Integrating Eqs. (24), (25), and (26) into Eq. (9), the critical crack (edge) size of the Ge substrate with the GaAs thin film can be calculated by an equation as follows:

$$a_c = 0.145 \times 10^{-10} (R/t)^2 \quad (27)$$

The critical edge crack sizes as a function of the bend radius for several thicknesses of a germanium substrate are plotted in Fig. 10. Since the K_{IIIC} value of germanium is not available, the equation for the critical crack size of a Ge substrate under twisting cannot be derived.

* $K_{IC} = (2E\gamma)^{1/2}$

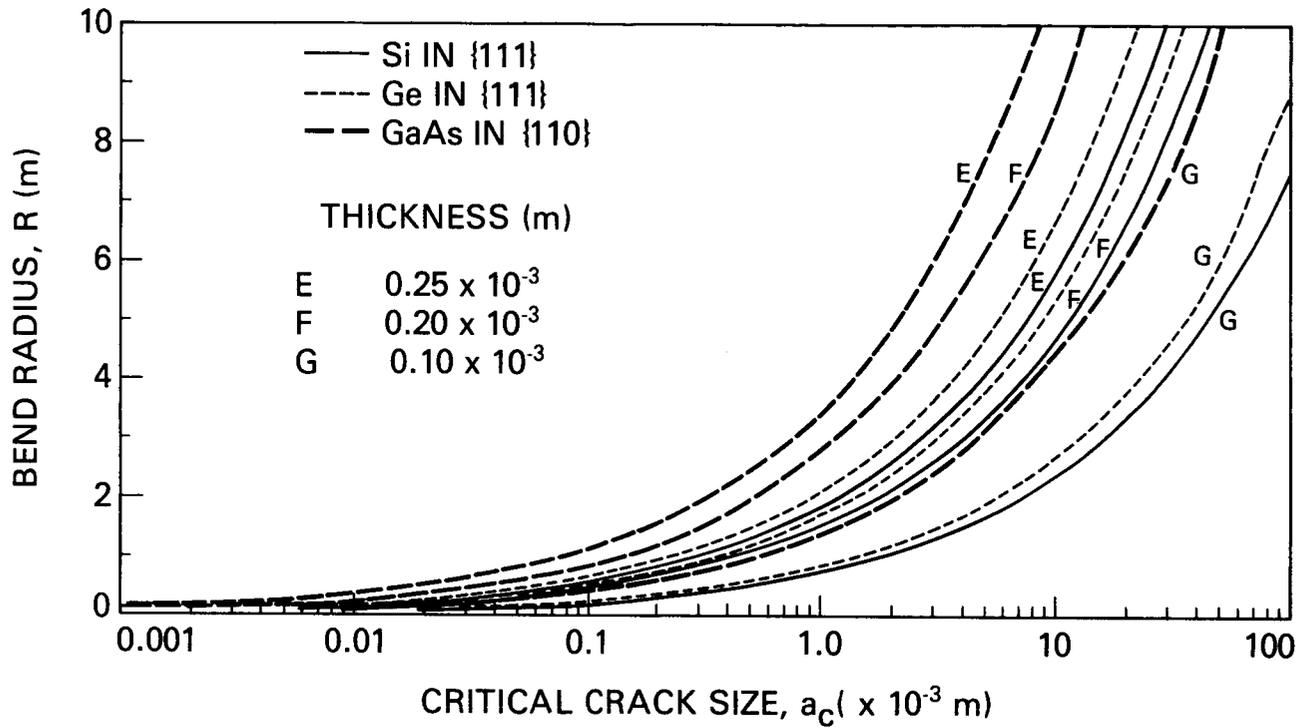


Fig. 10. Critical Crack Size as a Function of the Bend Radius for Several Thicknesses of a Germanium Substrate Compared With Those of Silicon and GaAs Wafers

IV. DISCUSSION

Analytical equations to calculate the critical crack size of a thin wafer under bending and twisting were derived by using fracture mechanics analysis and are expressed as follows:

For bending,

$$a_c = \frac{4(1 - \nu^2)^2}{\gamma^2 E^2} \left(\frac{K_{IC} R}{t} \right)^2 \quad (9)$$

For twisting,

$$a_c = \frac{(1 + \nu)^2}{\gamma^2 E^2} \left(\frac{K_{IIIC} R_{xy}}{t} \right)^2 \quad (14)$$

The important factors controlling the critical crack size in Eqs. (9) and (14) will be discussed in the following sections.

A. Cleavage Fracture

The typical Mode I fracture of silicon wafers subjected to cylindrical bending has been evaluated [7]. The fracture of {100} wafers under bending was found to be in the {111} planes. The Mode III cracking, as shown in Fig. 6, was also found to be in the {111} planes. Therefore, {111} is the easy cleavage plane for silicon under either bending and twisting. Similarly, the fracture of germanium was also observed [18] to have its cleavage plane in {111}.

The easy cleavage plane for GaAs was found [17] to be in the {110} planes. Cracking of GaAs wafers under twisting has not been evaluated. It is most likely that Mode III cracking for GaAs will be also on the cleavage plane {110}.

B. Edge Crack Versus Surface Crack

Referring to Eqs. (17) and (18) for Si, and Eqs. (19) and (20) for GaAs, in order to determine the minimum critical crack size in a wafer, the edge crack has been shown to be more critical than a surface crack. This suggests that edge finishing may be used to increase the strength of a wafer. Therefore, the discussion hereafter will be focused on the edge cracks.

C. Bending Versus Twisting

The critical crack sizes in a silicon wafer under bending versus twisting are given in Eqs. (9) and (14) and are plotted in Fig. 9. The critical edge crack

size in silicon wafers under twisting is approximately 2.61 times greater than that under bending, since the measured $K_{III}C$ value, shown in Table 1, is greater than the K_{IC} of silicon. Therefore, the cracks in a wafer subjected to bending are more critical than those in a wafer subjected to twisting.

D. Effect of Wafer Thickness and Bend Radius

As shown in Eqs. (9) and (14), the allowable critical crack size is proportional to the bend radius squared (R^2), but is in inverse proportion to the thickness squared (t^{-2}). In other words, a thinner wafer can be more flexible and can be bent into a smaller radius than a thicker wafer when the surface damage of these wafers is identical. Therefore, for a given loading, the allowable critical crack size in a thinner wafer is greater than that in a thicker wafer.

E. GaAs Versus Silicon and Germanium

The critical crack sizes (a_c) for Si, GaAs and Ge are expressed in Eqs. (18), (20) and (27), respectively, and plotted in Fig. 10 for several thicknesses as a function of bend radius. At any bend radius, the ratio of the calculated critical crack sizes of Si, Ge and GaAs of any given wafer thickness can be expressed as:

$$a_c(\text{Si}) : a_c(\text{Ge}) : a_c(\text{GaAs}) = 3.5 : 2.8 : 1$$

The difference between the critical crack sizes in Si and Ge wafers is small; however, the calculated crack size in the Si wafer is approximately 3.5 times greater than that in the GaAs wafer. This result is very important and suggests that the material standards on crack size for Si and Ge should not be applied to GaAs solar cells. GaAs wafers cannot be handled in the same manner as Si wafers.

F. Allowable Crack Size

The allowable critical crack size in the large-area wafers of semiconductors can be determined from Eqs. (9) and (14) if the required loading condition of a solar panel is given. The Jet Propulsion Laboratory (JPL) has made qualification tests of solar panels and suggested [19] that a minimum required pressure-load for a solar module is $2,400 \text{ N/m}^2$ (or 50 lb/ft^2 , equivalent to a 100-mph wind). The bend radius of a solar panel of 1 m (40 in.) in length, simply supported at two ends, was measured to be 2 to 3 m, depending upon the module construction. Assume that the solar cells in the module are bent into the same radius of curvature. Using Fig. 10, at bend radius of 2 m, the allowable critical crack sizes in a wafer with a thickness of $0.25 \times 10^{-3} \text{ m}$ (10 mils), as an example, are 0.33×10^{-3} , 0.9×10^{-3} and $1.1 \times 10^{-3} \text{ m}$ for GaAs,

Ge and Si, respectively. An edge chip of approximately 1 mm in a Si or Ge wafer may be easily observed. However, the critical edge crack of 0.3 mm in a GaAs wafer would be difficult for visual inspection. The exit chipping on the edge of semiconductor wafers is usually seen in I.D. sawing [20]. Edge finishing may be necessary to remove the exit chipping in GaAs wafers.

V. CONCLUSIONS

1. Analytical equations to determine the critical crack size of thin wafers under bending and twisting were derived by using the concept of fracture mechanics. These equations are expressed as follows:

For bending,

$$a_c = \frac{4(1 - \nu^2)^2}{Y^2 E^2} \left(\frac{K_{IC} R}{t} \right)^2$$

For twisting,

$$a_c = \frac{(1 + \nu)^2}{Y^2 E^2} \left(\frac{K_{IIIC} R_{xy}}{t} \right)^2$$

The cracks in a silicon wafer subjected to bending is found to be more critical than those in a silicon wafer subjected to twisting.

2. Edge cracks have been shown to be more critical than surface cracks. This indicates that edge finishing may be used to increase the strength of wafers.

3. The model suggested that for any given loading (bending or twisting), the allowable critical crack size in a thinner wafer is greater than that in a thicker wafer. In other words, a thinner wafer can be more flexible and can be bent into a smaller radius than a thicker wafer when the surface damage of these wafers is identical.

4. The calculated allowable critical crack sizes of Si, Ge and GaAs indicated that the difference between Si and Ge wafers is small. However, the critical crack size in a GaAs wafer is approximately 3.5 times smaller than that in a Si wafer under the same loading condition. This also suggested that GaAs wafers cannot be handled in the same manner as Si or Ge wafers. The material standards on the crack size for Si and Ge should not be applied to GaAs solar cells.

5. These models can provide a guideline for estimating the minimum allowable critical crack size of solar cells; e.g., under a pressure-load of $2,400 \text{ N/m}^2$ (~100 mph wind):

$$a_c (\text{GaAs}) \simeq 0.3 \text{ mm}$$

$$a_c (\text{Si}) \simeq a_c (\text{Ge}) \simeq 1 \text{ mm}$$

6. The analytical models were applied to Si, Ge and GaAs but would also be applicable to other materials using appropriate input data.

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<p>16. Abstract</p> <p>Although solar cells usually have chips and cracks, no material specifications concerning the allowable crack size on solar cells (e.g., Si or GaAs solar cells) are available for quality assurance and engineering design usage. Any material specifications that the cell manufacturers use have been developed for cosmetic reasons that have no technical basis.</p> <p>Therefore, the Applied Solar Energy Corporation (ASEC) has sponsored a continuing program for the fracture mechanics evaluation of GaAs. As part of this research program, the work described here was carried out in the Applied Sciences and Microgravity Experiments Section of the Jet Propulsion Laboratory for the ASEC.</p> <p>This publication utilizes fracture mechanics concepts to develop an analytical model that can predict the critical crack size of solar cells. This model indicates that the edge cracks of a solar cell are more critical than its surface cracks. In addition, the model suggests that the material specifications on the allowable crack size used for Si solar cells should not be applied to GaAs solar cells.</p> <p>In this report, the analytical model was applied to Si and GaAs solar cells, but it would also be applicable to the semiconductor wafers of other materials, such as a GaAs thin film on a Ge substrate, using appropriate input data.</p>			
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